FAILURE MECHANISMS OF HENS' EGGS

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ABSTRACT

The mechanics and mechanisms of failure of hens eggs have been examined experimentally under contact loading conditions. Eggs of known provenance were tested in compression between stiff platens, and the deformation modelled computationally as a Hertzian contact problem between a thin walled shell and a rigid plate. The associated contact damage was determined by scanning electron microscopy and by optical examination of transverse sections through the shell. Small stable micro-cracks were found to initiate in the contact area before ultimate failure, which was characterised by the propagation of one or more macroscopic cracks. The micro-cracks were not detected by routine visual inspection or acoustic resonance, and combined with inconsistent cuticle coverage such micro-cracks provide a pathway for pathogens to enter the egg contents and thus compromise egg safety.

1 INTRODUCTION

1.1 Industrial Context

The world laying hen population is currently estimated to be more than 4700 million. In 2001 world egg production was approximately 57 million tonnes and is estimated to exceed 70 million tonnes by 2015. Between 8 and 10% of these eggs suffer damage to the shell during routine handling. For each flock of 100,000 hens, 1% of cracked eggs reduces the income of a poultry farmer by $10,000 per annum, Hunton [1]. Cracked eggs are therefore of major economic significance to the production and marketing of eggs and constitute a risk to food safety.

1.2 Micro-structure

The microstructure and crystallography of eggshell has been described in detail by Solomon [2]. The structure of the eggshell which is illustrated in Figure (1) starts with the deposition of

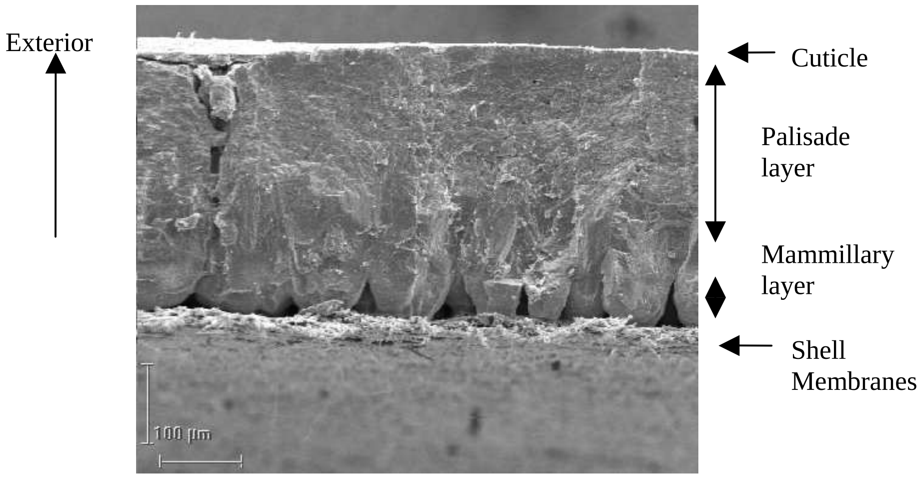

Figure 1: Transverse section of a hen's eggshell

a thick layer of egg white or albumen around the released ovum or yolk mass, and the deposition of paired shell membranes. The calcified shell subsequently forms on this template by the simultaneous deposition of calcium carbonate and organic matrix proteins on the outer membrane fibres. Calcification takes approximately 18 hours to complete and results in the formation of the mammillary, palisade and vertical crystal layers. Just prior to oviposition the proteinaceous cuticle is deposited onto the outermost surface of this calcified structure. The total thickness of the completed eggshell is approximately 320μm. Despite the complexity of its micro-structure, in the present context, it is appropriate to regard the eggshell as an isotropic thin shelled bio-ceramic structure whose shape approximates a prolate spheroid**.**

2 EXPERIMENTAL METHODS AND RESULTS

2.1. Mechanical testing

Eggs of known provenance were tested in compression between large flat metal platens at a displacement rate of 5 mm/min using a test machine fitted with a 100N load cell and an external extensometer. In equatorial compression tests, failure occurred at a maximum load of 34 ± 6N and at a load of 41 ± 8 N for axi-symmetric loadings applied across the poles. A number of tests were stopped before failure at maximum load. The eggs were unloaded and examined for cracks using acoustic crack detection equipment described by De Ketelaere *et al.* [3]. Twenty-four hours later they were candled for evidence of micro cracking. Samples of shell from the load sites were then carefully removed and examined by either light microscopy or scanning electron microscopy (SEM). For light microscopy, the sections were embedded edge-on in casting resin and polished using diamond paste to expose a transverse section. The inner surface of the shell (mammillary layer) was examined by SEM after removal of the shell membranes by plasma etching as described by Bain [4], while the outer surface of the shell was examined after removal of the waxy cuticle using EDTA.

Under compressive loading, eggs deform in an essentially linear elastic manner until the maximum load, when one or more macroscopic cracks extends radially from the load point causing an abrupt load drop and a loss of stiffness, as illustrated in Figure (2) . In the case of multiple macroscopic cracking, through thickness circumferential cracks may also develop as shown in Figure (3). However for both single and multiple macroscopic cracking, the radiating cracks eventually become stable and arrest a few centimetres from the load point. Subsequent loading causes the force to rise again, then fall as crack growth continues to extend and arrest, giving rise to the

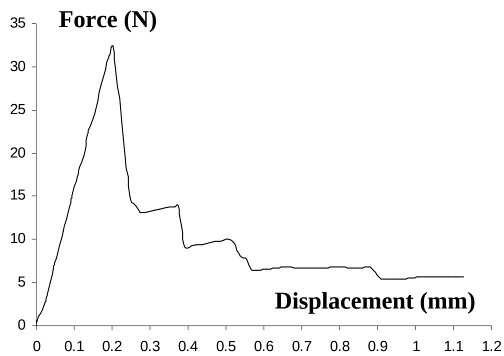

Figure (2) A representative Load – Displacement plot for an equatorially loaded egg

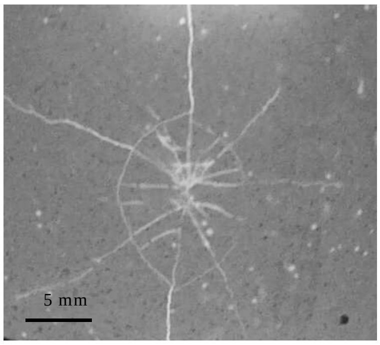

Figure (3) Macroscopic cracking on the outer surface at maximum load

typically serrated load displacement curve (Figure 2).
As the crack extends, the two shell membranes often separate. The outer membrane which is strongly bonded to the shell, tears, while the inner membrane remains intact. Combined with the loss of structural stiffness due to crack extension, the intact inner membrane favours crack arrest by transferring load from one side of the crack to the other. At loads significantly less than those required to cause macroscopic structural failure, a system of micro-cracks initiates from the inner surface of the shell by the separation of the mammillary bodies, as illustrated in Figure (4). A corresponding complex and irregular network of cracks subsequently develops between the mamillary bodies and propagates to the outer surface of the shell beneath the cuticle**.** This complex network of cracks extends over an approximately circular area with a diameter of the order of 1.5mm about the loading point. Before maximum load was attained, the outer surface frequently exhibited circumferential ring cracks, such as those shown in Figure (5).

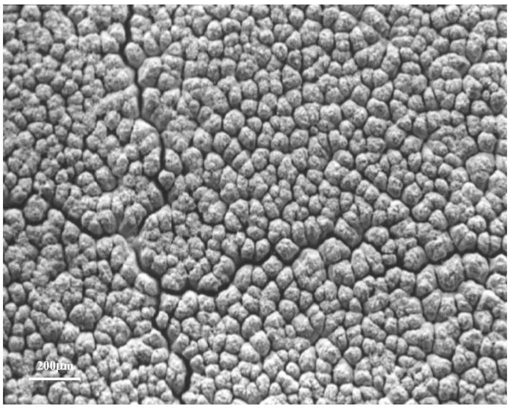

Figure (4). Cracks are initiated on the inner surface of the shell by separation of the mamillary bodies before failure at maximum load

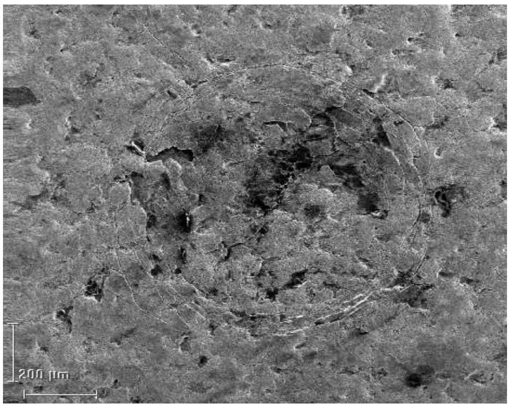

Figure (5) Circumferential cracking on the outer surface of the shell, after the cuticle has been removed

Polished sections such as that shown in figure (6) demonstrate that these circumferential cracks have a cone like shape (Roesler [5]), and frequently arrest part way through the shell thickness. In Figure (6) the series of small arrows indicate a through crack, which started from the inner surface of the shell by separation of the mammillary bodies shown in Figure (4). The larger arrows in figure (6) indicate stable conical cracks, which originate on the outer surface of the shell at the edge of the contact zone. At the edge of the contact area one side of the conical crack is displaced with respect to the other, but if the platen (or punch) diameter is greater than the contact area, the existing crack is unloaded and stabilises as the contact area increases and load is transferred to the next un-cracked annulus. This process repeats as loading continues, resulting in the concentric rings of circumferential cracks illustrated in figure (5). If the outer surface becomes highly damaged, a complete cone crack may also develop in the contact zone, (Figure 6). It is important to note that all three types of micro-crack shown in Figure (6) were induced at loads less than the maximum load and that none were detectable by routine visual inspection or by an acoustic resonance crack detector.

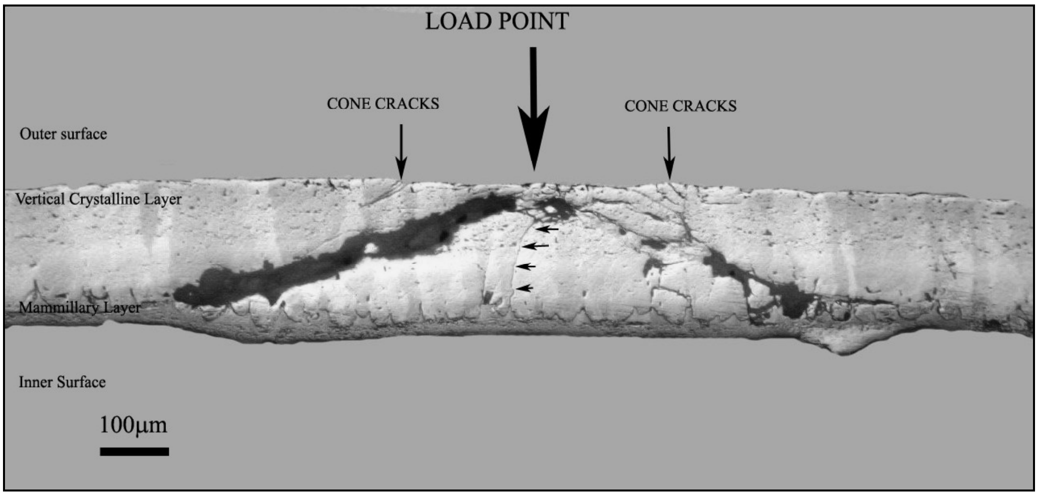

Figure (6) Transverse section showing micro-cracking mechanisms in the contact zone between the eggshell and a flat platen.

Mechanical tests were also performed using flat ended punches with diameters of 0.5, 1, 1.5 and 2mm. Punches with diameters of 1.5 mm in diameter or less, punctured the shell without causing a macroscopic crack to develop from the loading point. However punches with diameters of 2mm and above behaved as infinite flat platens and caused failure by macroscopic cracking. During punching failure, a conical tensile crack developed from the edge of the indenter and propagated through the shell, as a local tensile, rather than as a shear failure.

3 MECHANICS

The deformation of the egg shell under the flat platen was modelled using the finite element method as implemented in the code ABAQUS (Hibbitt, Karlsson and Sorensen 2003). The eggshell was modelled by axisymmetric second order isoparametric continuum elements with an isotropic linear elastic response, and also by first and second order shell elements. In this context, a shell is regarded as a thin structure which is capable of transmitting membrane forces and bending moments, Reissner (6). The stiffness during elastic deformation can be expressed in a

$$\frac{PR}{wEt^2} = C$$

form which derives from an analysis of a hemispherical shell by Koiter [7]:

The non–dimensional constant C was determined from the analysis to be 0.92 for equatorial loading in which P is the applied force E is Young's modulus, t the shell thickness and R is the mean radius and was only weakly dependent on the aspect ratio of the egg. Comparison of the stiffness with the experimental data allowed Young's modulus to be determined as 55 GPa which is close values for the modulus of calcite reported by Ashby and Jones [8], and is consistent with data from strain gauge tests.

The platen and egg initially make contact at a single point, and although this is mathematically acceptable, it is physically unrealistic. Point loading gives a good representation of the structural stiffness of the egg at small displacements, as shown in Figure (7) but fails to capture the detailed development of stresses, which initiate failure in the contact region between the shell and platen, when the force is distributed over a finite contact area at small loads, Johnson [9]. As a result , the contact was re-modelled as a non-linear problem using gap elements between a rigid platen and the eggshell. On this basis the development of the contact angle with applied load is illustrated in Figure (8). Failure loads of 34N corresponds to a contact diameter (2a) of 1.52mm. It is significant to note that punches with a diameter of 1.5mm or less puncture the shell without causing a macroscopic crack to propagate. While punches with a diameter greater than 1.5mm cause total failure by a macroscopic crack.

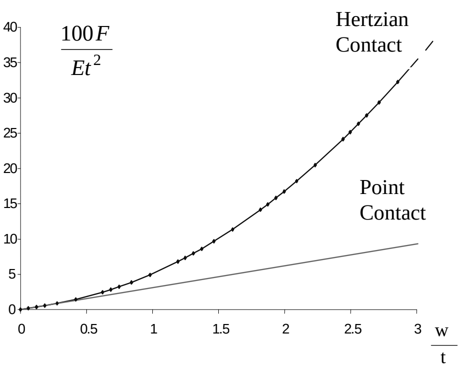

Figure (7) Calculated load –displacement relations for point loading and Hertzian contact at large levels of deformation

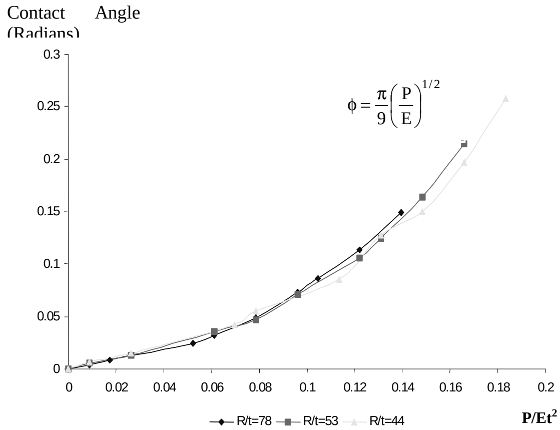

Figure (8) Contact angle as a function of non-dimensionalised load

Figure (9) shows the stresses on the inner surface of the shell under the central point of contact as a function of the applied load.

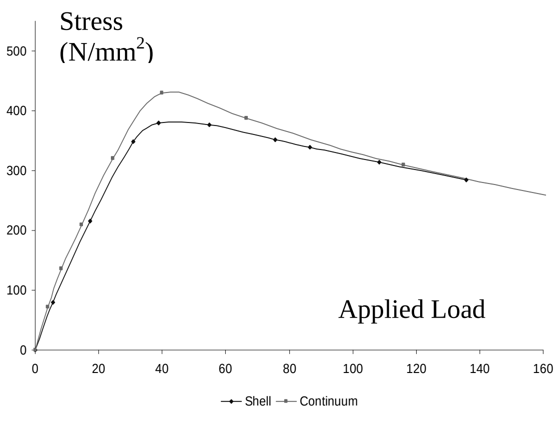

Figure (9) Stress under the initial contact point on the inner surface of the shell as a function of applied load

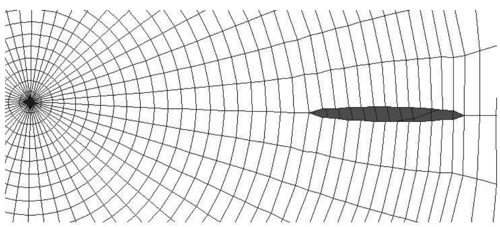

Figure (10) A crack from the pole to $\phi = 17.5^0$, is closed by membrane forces between $\phi = 0$ and 13^0

Here the analysis is presented using shell and continuum elements, both of which show the same trends. At a failure load of 34N, the stresses are very much greater than the local fracture stress of the eggshell. As a result the computational analysis confirms that cracks develop through the eggshell at loads very much less than the maximum load at which structural failure occurs. However, within the contact zone these cracks are stabilised by compressive membrane stresses. The membrane stresses cause the cracks within the contact area to close so that the effective crack length is restricted by closure close to the contact area. This is illustrated by Figure (10) where a crack which extends from the pole to $\phi = 17.5^0$, is closed between $\phi = 0$ and 13^0 . Outside the contact area, the sign of the meridional bending moment, $M_{\phi,}$ and the membrane force change, resulting in a tensile hoop stresses adjacent to the contact area. These tensile stresses cause these micro-cracks to open and become unstable resulting in structural failure of the eggshell. The load at which structural failure occurs is thus not determined by crack imitation, or by a weakest link argument, but rather by the toughness of the eggshell and the stability of cracks adjacent to the contact zone.

4 CONCLUSIONS

Mechanical tests, show that through thickness micro-cracks develop during mechanical contact at loads very much less than that required to cause macroscopic structural failure of the eggshell. Micro-cracks are formed by the high stress levels on the inner surface of the shell and propagate through the shell as it conforms to the shape of the platen. Conical micro-cracks are also formed at the outer surface of the shell at the edge of the contact zone. Punch tests demonstrate the importance of establishing damage over a critical area before macroscopic failure of the eggshell occurs at the maximum load when one or more of the micro-cracks becomes unstable. Combined with incomplete cuticle coverage, such micro-cracks provide a direct route for potentially harmful bacteria to enter the egg contents and thus compromise egg quality.

5 ACKNOWLEDGMENTS

The authors are pleased to acknowledge the support of the EPSRC through grant GR/R28915. ABAQUS was used under academic license from Hibbitt, Karlsson and Sorensen Inc.

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